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Published in:
Renewable & Sustainable Energy Reviews

DOI:
[10.1016/j.rser.2019.03.055](https://doi.org/10.1016/j.rser.2019.03.055)

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Document Version
Publisher's PDF, also known as Version of record

Publication date:
2019

[Link to publication in University of Groningen/UMCG research database](#)

Citation for published version (APA):

uit het Broek, M. A. J., Veldman, J., Fazi, S., & Greijdanus, R. (2019). Evaluating resource sharing for offshore wind farm maintenance: The case of jack-up vessels. *Renewable & Sustainable Energy Reviews*, 109, 619-632. <https://doi.org/10.1016/j.rser.2019.03.055>

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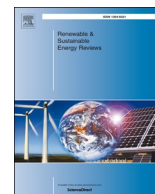
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Evaluating resource sharing for offshore wind farm maintenance: The case of jack-up vessels

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ARTICLE INFO

Keywords:

Resource sharing
Operations and maintenance
Offshore wind
Jack-up vessel
Simulation

ABSTRACT

Offshore wind energy is recognised globally as a viable alternative to finite energy sources. However, large cost reductions are still needed, particularly in the Operations & Maintenance (O&M) phase, which currently accounts for about 30% of the cost of offshore wind. For large component replacements, a jack-up vessel is often leased from the spot market, resulting in high costs and low utilisation. These costs can be lowered when multiple wind farm service providers would share the resources needed to employ jack-up vessels. In this paper, we analyse two types of resource sharing, as an alternative to each service provider leasing its own vessel: (i) vessel purchasing and sharing and (ii) the combined use of vessel and harbour sharing. We design a simulation model and include stochastic processes such as weather patterns and component failures. Results show that cost benefits up to 45% can be achieved compared to a leasing policy, depending on the number of wind farm service providers involved and on the geographical distance between offshore wind farms. Moreover, it is shown that the jack-up vessel should not be fully utilised to minimise costs. The performance benefits of harbour sharing in addition to vessel sharing are generally small, but become more significant if the network faces considerable congestion. Results are illustrated using a case study based on a setting in the Western North Sea.

1. Introduction

The rapid growth of energy demand and the recognised impact of fossil fuels on climate change have raised the importance of the production of renewable energy [47]. Globally, changes in governmental policies have sextupled investments in renewable energy during the last decade [16], leading to several innovations in the energy sector, particularly in the field of wind energy [49].

Offshore wind energy has become a viable alternative to finite energy sources, as the first bid based on zero subsidies has already been placed [14]. Offshore wind provides several advantages compared to onshore wind, such as higher output per turbine due to more consistent and stronger winds, limited visual pollution, and economies of scale due to wind farm size. However, offshore wind farms demand higher investments and wind turbines may suffer from relatively long and expensive downtime. As a result, their operational availability is in the range of 60–70%, opposed to 95–99% for onshore wind farms [37]. A critical area to improve the profitability of offshore wind farms is rethinking the Operations & Maintenance (O&M) phase that can account for up to 30% of the total expenditures of a wind farm [6,34].

An important part of the maintenance support organisation is the deployment of jack-up vessels. A jack-up vessel is a self-elevating barge, capable of raising its hull from the ocean's surface to provide a stable platform for heavy lifting and large component replacements [44]. Although jack-up vessels are necessary for offshore wind farms to carry out maintenance activities, their high chartering costs and long mobilisation times make it a challenging task to justify their use by a single owner/operator or maintenance service provider. As a consequence, both improved leasing strategies [12] and the shared use of vessels among adjacent wind farms (potentially maintained by different service providers), are recognised as viable options to reduce O&M costs [44].

In this paper, we evaluate the concept of resource sharing between service providers with regard to the use of jack-up vessels. By sharing a jack-up vessel, service providers can lower maintenance costs while increasing vessel utilisation, ultimately leading to a reduced cost of offshore wind energy provision. However, a resource sharing strategy comes with its own set of challenges. Firstly, the cooperating service providers, if too many, could have limited access to the shared vessel, which could result in long maintenance delays and a negative effect on turbine availability and costs. Secondly, each maintenance job at a

Abbreviations: CAPEX, Capital expenditures; O&M, Operations and maintenance; OPEX, Operational expenditures; VL, Vessel leasing; VS, Vessel sharing; VHS, Vessel and harbour sharing

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<https://doi.org/10.1016/j.rser.2019.03.055>

Received 3 August 2018; Received in revised form 22 March 2019; Accepted 25 March 2019

Available online 08 May 2019

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particular wind farm requires jack-up mobilisation and demobilisation activities (e.g., welding of components onto the vessel), which may be harder to conduct if service providers each operate from their own home harbour. Therefore this paper will also consider the concept of harbour sharing, whereby travel times can be reduced if demobilisation activities related to current jobs and mobilisation for new jobs can be executed in the same harbour.

We develop a simulation model of a wind farm maintenance system to assess the effectiveness of jack-up sharing policies compared to leasing. We consider weather conditions, failure rates, and operational parameters as to reflect real-world operations. The model is endowed with real-world data provided by industrial stakeholders. The remainder of the paper is structured as follows. In Section 2, we provide background information on the problem setting and discuss the relevant literature. In Section 3, we characterise the details of the simulation model. Section 4 presents the results, including an extensive sensitivity analysis and an illustrative case study of the potential effects of resource sharing between several offshore wind farms in the Western North Sea area. The results are discussed in Section 5.

2. Literature review

The design of cost-effective programs for maintaining offshore wind farms is challenging, due to the diversity of the different assets, unpredictability of deterioration and failures, poor accessibility, and a potential lack of resources such as personnel, tools and equipment, spare parts, and vessels. Moreover, since most offshore wind farms have been operating only for a few years, the industry lacks sufficient experience in terms of managing O&M activities and their optimisation [42].

The importance and complexity of offshore wind farm maintenance explain the high interest by researchers and practitioners alike. More than 70% of the reviewed publications on the topic date from 2012 or later, indicating its growing importance for the wind energy sector. We refer to Shafiee [38] for a relatively recent review. This review classifies offshore wind maintenance contributions into strategic, tactical, and operational decision areas. Strategic decisions concern wind farm design for reliability, location and capacity of maintenance accommodations, and selection of wind farm maintenance strategy. Tactical decisions include spare parts inventory management, maintenance support organisation, and purchase or lease of maintenance resources. The operational decision area consists of scheduling of maintenance tasks, routing of vessels, and performance measurements.

The deployment of vessels is recognised as a major cost factor throughout the lifetime of a wind farm. Several analyses incorporating vessel deployment are available, covering the installation phase [1,2] and the decommissioning phase [45]. With regard to the operational period of a wind farm, the deployment of vessels is crucial to guarantee access for maintenance activities. Also, vessel-related costs account for almost 45% of the total O&M cost [42]. Several papers have focused on improving decision making in either the selection or the allocation of the O&M fleet, composed primarily of crew transfer vessels (CTV) and jack-up vessels (research on service operation vessel use appears to be missing).

Dalgic et al. [10,12] provide decision support tools for the selection of a CTV fleet required to conduct maintenance for offshore wind turbines. Analogously, Sperstad et al. [42] test the robustness of six decision support tools for determining the size and composition of the CTV fleet, with the aim of reducing uncertainties to both modelling assumptions and input data. Halvorsen-Weare et al. [18] study the vessel fleet optimisation problem. The proposed optimisation model indicates which vessel types should be either purchased or chartered-in, and which infrastructure is needed (e.g., onshore ports and helicopter bases). Using simulation, Sperstad et al. [41] analyse CTV fleet size and mix, timing of jack-up vessel heavy maintenance campaigns, and timing for preventive campaigns. Results indicate that jack-up strategies are

the most costly, and also that CTV and jack-up vessel decisions can be disconnected. From a more operational point of view, Dalgic et al. [11] develop a simulation tool to improve resource allocation costs (which may include helicopters, CTVs, and jack-up vessels) to support day-to-day O&M activities.

Historically, the requirement for jack-up vessels was determined by the size and number of installations of offshore wind farms. But as assets deteriorate and the number of megawatts installed increases, the market is in need of more and more heavy lifting equipment for maintenance operations. McMillan and Dinwoodie [30] develop a forecasting model for the demand of jack-up vessels for the period 2012–2030, based on installed capacity and reliability figures, and failure duration data of turbines. Results indicate a significant expected increase in demand in the analysed period.

Due to the cost of purchasing jack-up vessels and their scarcity in the spot market, there has been a growing interest in optimising chartering strategies. However, chartering entails a few drawbacks, such as unreliable lead times and difficulties in planning maintenance [38]. Several contributions are available on the subject. Dalgic et al. [9] provide a classification of existing jack-up vessels and estimate charter rates in different periods of the year. The aim is to better plan maintenance operations while considering different chartering options. Stålhane et al. [43] develop a stochastic mathematical model to decide when and for how long a jack-up vessel should be chartered. Their work provides a tactical level perspective, indicating the time when to charter the vessel and considering the possibility to charter in several shorter intervals each year.

Dalgic et al. [13] investigate optimal jack-up vessel chartering strategies in terms of the charter type and the charter period, for 100, 200, and 300-turbine cases. Their analysis compares short-term chartering strategies, where the vessel is leased from the spot market, with long-term chartering. The long-term charter is modelled as a bareboat charter, assuming that costs related to chartering consist of fuel, crew expenses, salary cost (including management), and vessel O&M cost, next to the daily charter rate. They find that a long-term charter is feasible only for larger wind farms. Moreover, due to uncertainty in the chartering time, a leasing strategy may lead to very long mobilisation times. The authors, therefore, suggest that jack-up purchasing can be cost-effective for larger wind farms when there are sufficient turbines to warrant the capital expenditure. Furthermore, they suggest a further investigation of the cost benefits of regional collaboration between wind farms as a direction for future research. The Crown Estate [44] points out that significant delays to heavy lifting operations for maintenance can arise from the following activities: chartering a vessel, delivering spare parts to harbour, mobilising the vessel, sea transit, preparing the turbine for component replacement, component elevating operations, re-commissioning the turbine, and demobilising the vessel (see Fig. 1). Furthermore, the weather window must be considered when planning maintenance since the duration of a window is often not sufficient for large component replacement.

It is known that horizontal alliances may lead to significant cost reductions and several other benefits [3,40,48]. However, literature on resource sharing in offshore wind settings is scarce. Irawan et al. [19] consider the cost-saving potential of sharing CTVs and technicians among wind farms that are served from the same harbour. Schrottenboer et al. [36] study technician sharing among wind farms served from different harbours. Their results show that maintenance cost and turbine downtime can be reduced while fewer vessel trips are required. Moreover, The Crown Estate [44] provides an overview of the role of jack-up vessels and suggests that regional collaboration may lead to large cost savings and reduced delays. To the best of our knowledge, the only study on jack-up sharing in the offshore wind sector is the work of Beinke et al. [5], who investigate the benefits of resource sharing during the installation phase. Although the above studies consider resource sharing, a study that focuses on jack-up sharing during the operational phase is missing.

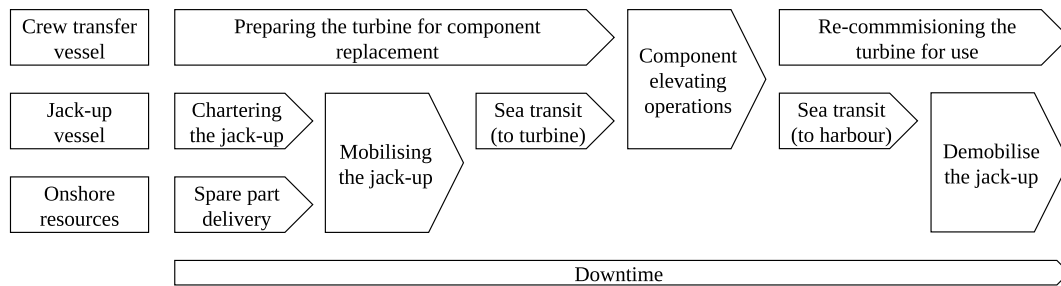


Fig. 1. Overview of jack-up related processes and potential delays (based on The Crown Estate [44]).

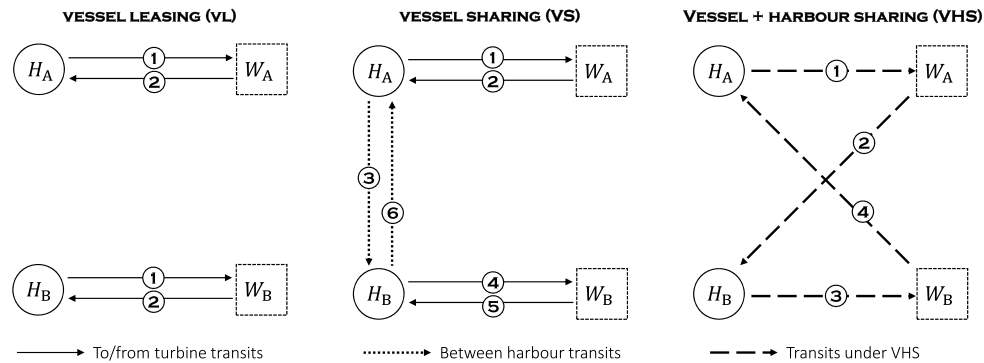


Fig. 2. The three studied policies (number order indicates the sequence of events).

3. Simulation model

3.1. Setting and resource sharing policies

In this paper, we address regional collaboration with a resource-sharing perspective. The problem presents a trade-off between the total cost of maintenance (for any replacement requiring jack-up vessels) and cost of maintenance delay. By sharing vessels, service providers are no longer dependent on leasing from the spot market, which will eliminate the chartering time and reduce turbine downtime. In addition, sharing harbours eliminates unnecessary transfers between otherwise separate harbours (where demobilisation and mobilisation take place). As the number of participating wind farm service providers increases, the individual cost of maintenance may decrease. However, the likelihood of service providers simultaneously placing demand upon the jack-up increases as well, which may result in higher downtime costs. It is expected that an optimal trade-off exists on the total cost curve. Moreover, weather conditions have an impact on performance, irrespective of the resource sharing policy. Specifically, weather may impose considerable working restrictions on the timing of transits, jacking up and down, and replacement activities [22].

Finally, note that throughout this paper we will predominantly refer to the *service provider* as the party that carries out the maintenance work for a single wind farm, and leases or owns the vessel. This is acceptable as the main focus of our work is cost and wind farm availability. In reality, the roles of owner–operator–service provider may not overlap, in which case the contractual agreements between parties become a decision of concern.

3.1.1. The setting

We consider maintenance actions that require a jack-up vessel, such as replacements of blades, gearboxes, generators, and transformers, similar to the work presented by Dalgic et al. [12]. Following several other papers in the offshore wind domain, it is assumed that components are replaced upon failure (i.e., corrective maintenance). Firms such as Siemens label these kinds of jobs as *major corrective work* [39].

Focusing on corrective maintenance is reasonable considering that preventive maintenance, for instance by means of advanced condition monitoring techniques, is notoriously difficult in the offshore wind sector. In particular, each of the different condition monitoring techniques appears to be having specific disadvantages [4]. For instance, some condition monitoring techniques are able to detect incipient failures only shortly before they occur [20], which significantly limits its applicability. Moreover, zooming in on corrective maintenance allows a comparison with papers such as [12].

This paper studies a setup with two or more offshore wind farms, which are maintained by different service providers who each operate from their own harbour. Within the harbour, mobilisation activities are needed to prepare the vessel for departure and loading the necessary parts on board. Demobilisation activities are carried out upon return (e.g., remove excess welding) to get a vessel ready for the next mobilisation task. Upon departure, it is exactly known which parts to bring offshore as all the jobs to be carried out are known in advance. Spare part lead time, the cost of onshore transportation, and warehousing are not considered in this paper.

3.1.2. Considered policies

We study three policies with different degrees of resource sharing, called *vessel leasing* (VL), *vessel sharing* (VS), and *vessel + harbour sharing* (VHS). A graphical overview of the three policies is depicted in Fig. 2. Under the vessel leasing policy, there is no resource sharing and the jack-up is leased from the spot market.

Under the VS policy, multiple service providers collectively purchase a single jack-up vessel which is used to perform all replacements for all the wind farms. The jobs are carried out in a first-come-first-serve order. However, when the jack-up visits a wind farm, multiple replacements can be executed within this visit in a quasi-opportunistic sense. For example, consider two wind farms W_A and W_B . Suppose turbine T_1 in wind farm W_A fails, followed by turbine T_2 in wind farm W_B , followed by turbine T_3 in wind farm W_A . Then the jack-up starts a campaign to replace the component belonging to turbine T_1 , but is also allowed to opportunistically replace the failed component of turbine T_3 .

This avoids unnecessary high downtime for T_3 caused by additional mobilisation and demobilisation activities and travel delays. However, if the weather conditions only allow for a campaign long enough to replace the first component, then it is not allowed to postpone the entire campaign until the weather allows to replace both components in a single visit. When a campaign is finished, the jack-up returns to the same harbour as where it departed from.

The VHS policy is similar to the VS policy, except that the demobilisation can be performed in any harbour. Thus, if a new failure has occurred in a wind farm maintained by another service provider, then the jack-up does not return to the harbour where mobilisation has been carried in order to demobilise, but directly sails to the next harbour where both demobilisation and mobilisation are carried out. That is, under this policy it is not necessary for the jack-up to return to the harbour it departed from. If there are no new jobs, then the jack-up returns to the harbour where the last mobilisation has taken place.

3.2. Order of events

In this section, we first give a brief overview of the events under each policy. Thereafter, these steps are explained in more detail. Upon failure, a wind turbine is immediately inspected. When the inspection reveals that a jack-up is required we have, under the VL policy, the following order of events: lease the jack-up from the spot market, mobilise the jack-up in the harbour, transit to the wind farm, replace the component, transit back to the harbour, demobilise the jack-up, and return the jack-up to the owner.

The VS and VHS policies have the same order of events except that, instead of having a chartering process, a service provider might have to wait for the vessel to arrive from its previous location. Under the VHS policy, as mentioned in the previous section, transits between harbours are not always necessary since the vessel may travel directly to the next harbour after finishing a job offshore.

3.2.1. Inspection and preparation

When a failure occurs, an offshore maintenance crew inspects whether a jack-up vessel is needed or that smaller vessels can perform the necessary maintenance. The inspection time is labelled as τ_{inspect} . When a jack-up is required, another maintenance crew is sent out to prepare the turbine for component replacement. The replacement of the component cannot start until this preparation is finished. The preparation time is labelled as τ_{prep} . The simulation approach regarding the time of failure of the four wind turbine components is explained in Section 3.4.

3.2.2. Chartering time

Consider the VL policy. A jack-up is only chartered if there is a minimum number of jobs available in the wind farm (referred to as the batch size threshold). This threshold is set by the service provider in order to cluster jobs and thereby avoiding excessively high chartering costs. In our study, the batch size threshold will be optimised for the considered parameter settings. The chartering time τ_{charter} is the time between searching for a vessel on the spot market and the arrival of the vessel in the harbour. There is significant uncertainty in the chartering time due to an insufficient number of available jack-up vessels [12]. As there is insufficient knowledge available of the chartering process, we interviewed several industry experts to obtain estimates of the minimum, maximum, and most likely chartering time. Doing so allows us to use a triangular distribution function, from which the random chartering times are drawn.

Under the VS and VHS policies, there is no chartering time but the service provider has to wait for the vessel to arrive either from the wind farm where the last job is carried or from the harbour where it is currently situated. The waiting time is zero if the vessel is present in the harbour where mobilisation will be done.

3.3. Mobilise time in harbour

If a vessel has arrived and is ready for mobilisation, a mobilisation time is required to sea fastening (i.e., welding) spare parts on the vessel to prevent spare parts from moving during transit. Each campaign has a mobilisation time τ_{mobilise} , which we assume to be constant regardless of the number of components to be brought on board.

3.3.1. Travel time with possible weather delay

The travel speed v of a jack-up is assumed to be constant and is thus not affected by weather conditions. The distance between location i and j is denoted by d_{ij} and thus the travel time equals $t_{ij} = d_{ij}/v$. The jack-up only departs when the weather forecast (see Section 3.4) states that the vessel can safely reach the offshore wind farm and also has enough time to transit back to the next harbour, that is, the maximum wave height and wind speed at sea level do not exceed the thresholds ω_1 and ω_2 , respectively.

3.3.2. Maintenance time with possible weather delay

Upon arrival at the wind farm, the vessel jacks up into a stable position. This can be done safely if during the jacking up time τ_{jackup} the wave height and wind speed at sea level do not exceed the thresholds ω_3 and ω_4 , respectively. Note that generally $\omega_1 > \omega_3$ and $\omega_2 > \omega_4$. Work (i.e., lifting operations and replacements) can commence if the preparation of the turbine has finished and the weather conditions remain stable, that is, wave height and wind speed at sea level do not exceed ω_3 and ω_4 . In addition, the wind speed at hub level may not exceed ω_5 during the replacement time τ_{replace} . Otherwise, the vessel waits until wind speed at hub level is below ω_5 . Work is carried out for 24 h per day using multiple crews. After the (last) job has finished, the vessel jacks down and starts the journey back to shore. Jacking down can be done if during the jacking downtime τ_{jackdown} wave height and wind speed at sea level do not exceed the thresholds ω_3 and ω_4 .

It is possible that bad weather occurs between activities (e.g., between jacking up and the lifting operations). This is allowed as long as the waiting time between consecutive activities does not exceed 24 h and the survivability restrictions are satisfied. If longer windows with bad weather are foreseen, the jack-up vessel will not depart at all.

3.4. Travel back and demobilise

The restrictions for travelling back are similar to the transit to the wind farm. After arrival of the vessel in the harbour, demobilisation activities (e.g., remove weldings) are needed either to properly return the vessel to the leasing company, or to prepare the vessel for the next mobilisation tasks. The total demobilisation time $\tau_{\text{demobilise}}$ is a constant and is assumed not to be affected by the number of components brought on board.

3.5. Output

Output measures include the yearly cost per wind farm, the availability per wind farm, the mean and maximum downtime, and the vessel utilisation. Under the VL policy costs include chartering cost, lease costs, fuel costs, replacement cost, and revenue losses. Under the VS and VHS policies, a one-time capital expenditure (CAPEX) and yearly operational expenditures (OPEX) are incurred instead of chartering and lease costs. The revenue losses are calculated as the lost production during periods of downtime. Similar to other studies (e.g., [26]), we assume a power curve as shown in Fig. 3. For the sake of simplicity, we linearised different segments on the curve. The cut-in speed is the minimum wind speed needed for electricity generation, the rated speed is the wind speed at which maximum production is reached, and the cut-out speed is the maximum wind speed above which the turbine is disconnected out of precaution.

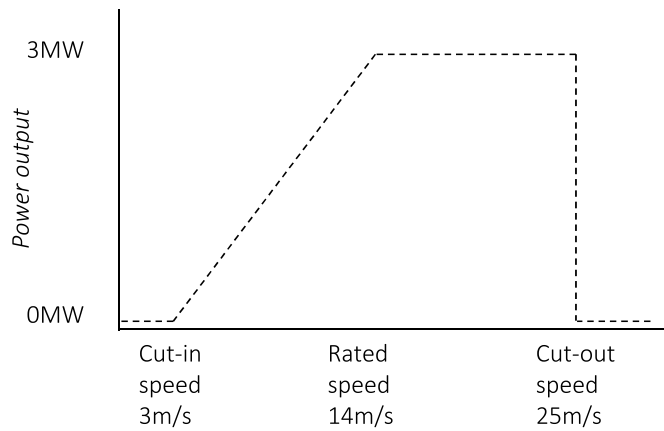


Fig. 3. Power curve of a 3 MW turbine.

3.6. Weather and failure simulation

To analyse the performance of the three policies, it is assumed that most of the parameters in the model are deterministic. Exceptions include the chartering time (see Section 3.2.2 and 4.1), weather conditions, and failures of the components. In this section, we elaborate on the latter two, whereby we follow the approach given in [12].

The weather conditions are simulated by using 14 years of data (2004–2017) obtained from the FINO-platform.¹ The dataset provides wave heights (hourly intervals) and wind speeds (10-min intervals) measured at several altitudes, including a measurement at 33 m and 100 m above sea level. To obtain an estimated wind speed at sea level, we extrapolate the observation according to the wind power law [15], given by

$$v_2 = v_1 \cdot \left(\frac{h_2}{h_1} \right)^\alpha,$$

where v_i is the wind speed at altitude h_i , and α is the shear parameter that depends on atmospheric conditions such as temperature and humidity [27]. A shear value of $\alpha = 0.1$ is commonly used for offshore locations [7].

In the simulation, years of data (i.e., wave height and wind speed) are randomly drawn from the data set. Hereby the typical offshore weather characteristics such as strong seasonality effects and the correlation between wave height and wind speed are preserved.

Component failures are simulated with a constant failure rate, which is a common way of modelling failures for offshore wind turbine components [29]. We note that a failure of any component immediately results in a complete stop of the turbine, and, as a result, the other components of the turbine do not fail until the turbine is operational again.

4. Results

We first introduce the parameter values considered in this study. Thereafter we discuss the cost savings obtained by the sharing policies compared to the VL policy. The robustness of the insights are tested in an extensive sensitivity analysis, and we conclude the section with a case study that analyses the potential cost savings for various possible collaborations in the Western North Sea. The results are obtained from the simulation model which is implemented in C++17. The implementation uses common random numbers and all tables and figures are the result of 2000 repetitions.

4.1. Implementation and model parameters

Our base setting consists of several wind farms that each have fifty 3 MW turbines with a hub height of 100 m. The distance between a wind farm and its corresponding harbour is 100 km, and the distance between adjacent harbours is set to 75 km. To convert cost data from British Pounds to Euros, we assume 1 GBP = 1.125 EUR. In terms of shear value we set $\alpha = 0.1$.

Turbine-specific parameters such as failure rates and replacement costs are given in Table 1. Considering failure data it is important to note, similar to [12], that reliable turbine data is scarce. We, therefore, rely on failure data reported in [24]. Note also that component replacement takes considerable time, in particular replacement of the gearbox and transformer. Considering replacement cost as well, it is clear that the gearbox is a particularly critical component in the system.

Table 2 gives an overview of the weather restrictions that apply to the jack-up vessel. The table shows that operability conditions for jacking operations are stricter than survivability conditions in terms of wave height and wind speed at sea level, while an additional restriction in terms of wind speed at hub level is needed for lifting operations.

Table 3 provides an overview of the remaining time and cost parameter data, vessel data as well as miscellaneous data such as the electricity price. With regard to the time parameters, we assume that most are deterministic, with the exception of τ_{charter} , which, according to [12], may vary significantly depending on factors such as seasonal availability. Mobilisation is assumed to take 24 h, regardless of the number of components to be brought along. Note that the preparation time τ_{prepare} is less than then mobilisation time $\tau_{\text{mobilisation}}$, suggesting that work can always start once the jack-up vessel has arrived at the wind farm. It is therefore not necessary to explicitly consider preparation time in the simulation model. We assume a maximum weather delay between offshore operations of 24 h, which means that one particular activity (e.g., lifting) has to start within 24 h after the previous activity (in this case jacking up) has finished. If a weather delay of more than 24 h offshore is foreseen, the vessel will not depart to the wind farm.

With regard to the vessel data, note that a maximum of three components can be brought offshore, which limits the number of jobs that can be carried out to three. Next, similar to other papers, the costs of chartering or purchasing a vessel are significant. It is assumed that the wind farms have a life span of twenty years, which means that capital expenditures are € 7,500,000 per year under the VS and VHS policy, for all participating wind farms combined.

Most parameter data are drawn from [12] and [11]. To verify the validity of model assumptions and parameter values, and to complement the dataset with respect to new parameters, we conducted several interviews with industry experts (including a leading energy research centre and turbine manufacturer). This led to several additions and changes. Inspection and preparation time were found to be important in the literature and are considered relevant by experts, but were missing in [12] and [11]. The interviews also alerted us to consider a maximum delay between offshore activities. In addition, the expert interviews led to some minor changes with respect to the cost of leasing (chartering cost and day rate) and owning jack-up vessels (CAPEX and OPEX). We set the electricity price at € 100.00 per megawatt hour, which is arguably more in line with current offshore wind prices. Finally, in line with practice, we set the restrictions for lifting operations more conservatively than [12]. Note that although the parameter values were chosen with care, actual values may be different in specific settings. Therefore we test the sensitivity of the main findings with respect to model parameters later on.

4.2. Results of the base case

This section compares the performance of the three policies when these are applied to the base case. Recall that the VL policy only charts a jack-up if there is a minimum number of jobs in the wind

¹ Data can be requested via <https://www.fino1.de/en/>.

Table 1

Component specifications such as price and failure rates (as given in [12]).

Component	Failure rate per 10 ⁶ h	Replacement time τ_{replace} (h)	Replacement cost (€)
Blade	0.55	24	84,375
Gearbox	5.48	144	450,000
Generator	5.48	72	135,000
Transf.	1.73	144	47,250

Table 2

Weather restrictions for the jack-up vessel (as given in [12] except for the lifting restriction).

	Survivability	Operability	
		jacking	lifting
Wave height (m)	$\omega_1 = 10.0$	$\omega_3 = 2.8$	–
Wind speed at sea level (m/s)	$\omega_2 = 36.1$	$\omega_4 = 15.3$	–
Wind speed at hub level (m/s)	–	–	$\omega_5 = 16.0$

Table 3

Main model parameters (base case).

Parameter	Value base case
<i>Time parameters</i>	
τ_{inspect}	10 h
τ_{prepare}	20 h
τ_{charter} (best, likely, worst case)	{168, 1440, 2880 h}
τ_{mobilise} , $\tau_{\text{demobilise}}$	24 h
τ_{jackup} , τ_{jackdown}	3 h
Maximum delay between offshore activities	24 h
<i>Vessel data</i>	
Travel speed v	11 knots
Vessel capacity (max. number of components)	3 components
Minimum leasing period	30 days
<i>Cost parameters</i>	
Chartering cost (VL only)	€ 350,000/charter
Lease day rate (VL only)	€ 125,000/day
CAPEX (VS/VHS)	€ 150,000,000
OPEX (VS/VHS)	€ 10,000,000/year
Fuel consumption in port	2 metric tons/day
Fuel consumption in operation	10 metric tons/day
Fuel charge	€ 618,75/metric tons
Power curve parameters (cut-in, cut-out speed)	3 m/s, 25 m/s
Maximum production reached at	14 m/s
Electricity price	€ 100.00/MWh

farm (see Section 3.2.2). The optimal batch size threshold for the considered base case equals two jobs. Table 4 gives, for various possible coalitions, an overview of the cost benefits, wind turbine downtime, and the vessel utilisation for each policy. The two resource sharing policies can realise significant cost savings and availability benefits, and reduce turbine downtime due to the absence of the lengthy chartering

Table 4

Results of the base case under the three policies for various coalitions.

	Yearly costs per wind farm	Cost benefit	Availability	Mean downtime	Max downtime	Vessel utilisation
Vessel leasing	€ 12.00·10 ⁶	–	97.3%	2114 h	8123 h	–
<i>Three wind farms</i>						
Vessel sharing	€ 8.21·10 ⁶	31.9%	99.2%	592 h	2814 h	59.1%
Vessel + harbour sharing	€ 8.21·10 ⁶	31.9%	99.2%	590 h	2808 h	59.0%
<i>Five wind farms</i>						
Vessel sharing	€ 6.52·10 ⁶	45.9%	98.2%	1367 h	4710 h	89.4%
Vessel + harbour sharing	€ 6.49·10 ⁶	46.1%	98.3%	1340 h	4663 h	89.1%
<i>Seven wind farms</i>						
Vessel sharing	€ 9.95·10 ⁶	17.4%	91.8%	6710 h	13566 h	99.5%
Vessel + harbour sharing	€ 9.86·10 ⁶	18.2%	92.0%	6592 h	13399 h	99.5%

process. Interestingly, with a larger number of wind farms participating (i.e., five wind farms compared to three), maximum turbine downtime can increase under resource sharing due to congestion of multiple failures in the system but this does not outweigh the benefits of resource sharing.

The benefit of VHS over VS is the possible reduction in travel times between harbours. However, this only occurs if there are jobs available in a wind farm served from another harbour before the vessel transits back from the wind farm. For small coalitions, there is little congestion, and as a result, the benefit of VHS over VS is negligible.

Fig. 4 gives an overview of how the different policies behave in terms of the various performance metrics, and how these metrics vary with respect to the number of participating wind farms. Naturally, the curve belonging to the VL policy is flat as with this policy each wind farm is serviced by a separate jack-up. Hence, each wind farm has a similar performance in terms of cost and jack-up utilisation. The VS and VHS policies behave similarly under these parameter settings, therefore only the curves for the VS policy are shown.

Under the VL policy, the yearly cost per wind farm is approximately € 12,000,000. Clearly, vessel sharing (i.e., the VS policy) can significantly reduce costs if between three and seven wind farms collaborate. Under the current parameter settings, five participating wind farms is the observed minimum in the simulation when it comes to yearly cost per wind farm.

Under the current parameter settings, the lowest cost is reached with five participating wind farms. However, when looking at the cost curve of the VS policy, it can be noted that yearly costs are approximately equal if four, five, or six wind farms participate in the coalition. Nevertheless, the coalition might have a preference for slightly fewer participating wind farms (e.g., four wind farms), as the second graph clearly shows that jack-up utilisation significantly decreases when fewer wind farms participate, implying higher responsiveness to failures.

Fig. 5 shows a cost breakdown under the VS policy. The vertical line displays the interval between the 1% and 99% percentile of the total yearly costs. The figure shows that capital and operational expenditures per wind farm decrease if more wind farms participate in the coalition, while replacement and fuel costs remain relatively stable. Interestingly, jack-up sharing does imply that some revenue losses have to be accepted, as Fig. 5 shows that revenue losses grow as more wind farms participate in the coalition. In particular, if five wind farms participate, then about one-fifth of the yearly cost per wind farm is due to revenue losses. Moreover, the volatility of the realised yearly costs rapidly increases for coalitions with six or more wind farms due to the possible congestion that arises if multiple wind farms require the jack-up simultaneously.

Fig. 6 gives a breakdown of the jack-up vessel utilisation. Indeed, according to the figure, if fewer wind farms participate, vessel idle time (which is measured as the time the vessel is idle in some harbour) increases which benefits responsiveness at only slightly increased cost. Fig. 4 shows that a smaller number of wind farms leads to lower mean-

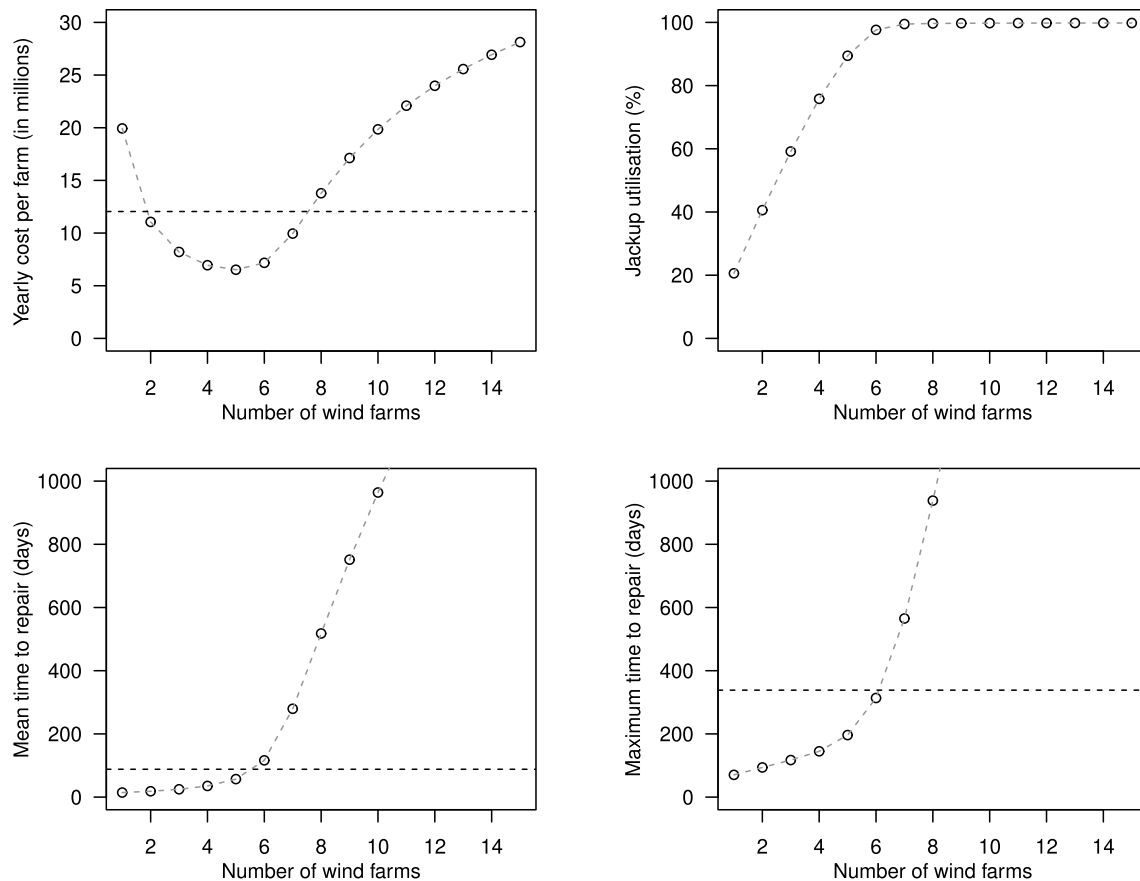


Fig. 4. Effect of number of wind farms on performance metrics under the VL policy (flat curve) and VS policy.

time-to-repair and also the risk of having significant time to repair is reduced (i.e., the maximum time to repair decreases). Regardless of the exact number of participating wind farms around the cost minimum, it is clear from Fig. 6 that significant vessel idle time is needed for cost minimisation purposes (i.e., the jack-up vessel should be less than fully utilised).

Summarising, the results of the base case show that vessel sharing is a feasible and a profitable policy for offshore wind farm maintenance, provided that a coalition of wind farm service providers of the right size can be found. In the next section, we zoom in on the sensitivity of these results with respect to some critical model parameters.

4.3. Sensitivity analysis

We continue with a sensitivity analysis in which we change various parameters one by one while studying the effect on the yearly costs, the optimal coalition size, and the optimal batch size threshold. Besides studying the yearly costs under the optimal coalition size, we also examine how costs behave for a given coalition in order to study the effects of determining a coalition based on wrongly estimated parameters. The optimal batch size threshold is not shown since a threshold of two jobs appears to be optimal for nearly all considered cases. Furthermore, in order to keep the figures concise, the results of the VHS policy are not discussed in this section as these are similar to the results of the VS policy.

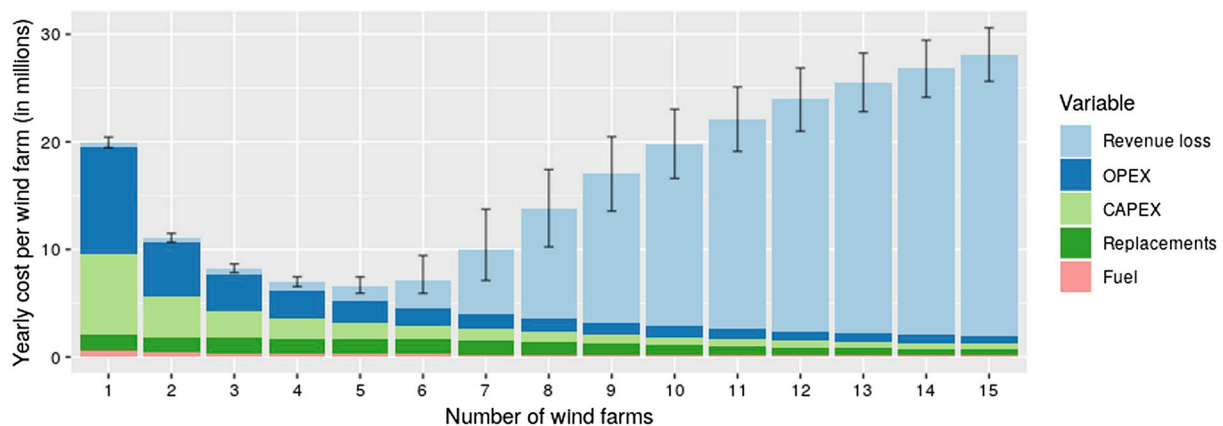


Fig. 5. Total expected yearly costs per wind farm under the VS policy. The mean of the yearly costs per wind farm are statistically different (Welch's t-test: p-value <0.001). The vertical line displays the interval between the 1% and 99% percentile of the total yearly costs.

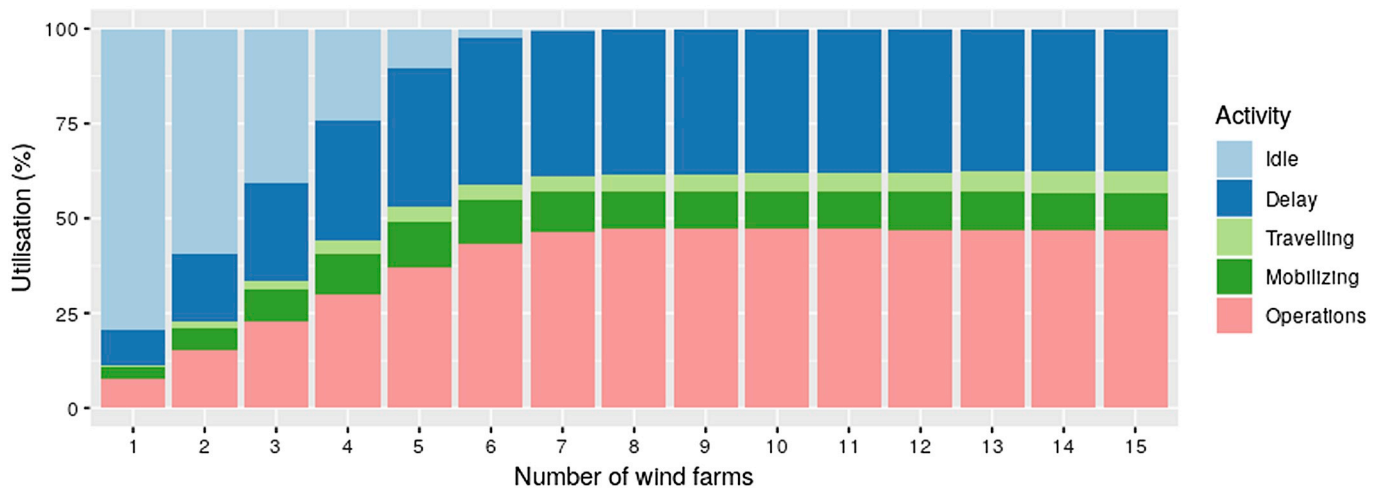


Fig. 6. Jack-up utilisation and contributing factors under the VS policy.

We consider parameters that are inherently uncertain such as the failure rate of components, and various cost parameters that are naturally volatile such as electricity and fuel prices. We also vary parameters that are a priori known with certainty such as distances between ports, to reveal settings in which resource sharing is most promising. For each parameter value, we study the coalition size n_{wf} (i.e., the number of wind farms that share a jack-up together) and the batch size threshold m (i.e., the minimum number of failures before for leasing a jack-up) that result in the lowest yearly cost per wind farm. The results are obtained by varying a parameter over a specified range. Then, for each parameter setting, the simulation is repeated 2000 times with n_{wf} ranging from 1 to 15 and m ranging from 1 to 3. So, a graph that presents costs for 100 parameter values is the result of $100 \times 15 \times 3 \times 2000$ simulations in total.

4.3.1. Failure rate and replacement duration

The failure behaviour of components is relatively uncertain due to the lack of long-term experience with offshore wind and because turbines rapidly continue to develop, resulting in unpredictable failure behaviour for newly developed turbines. The time required to replace components can be influenced by training technicians and by developing components that are easier to replace. To examine how this affects the optimal decisions, we range the characteristics of the components with the lowest (i.e., blades) and highest (i.e., gearboxes) estimated failure rates.

Fig. 7 depicts how the failure rate of blades (top) and gearboxes (bottom) affect the expected yearly costs (left), the optimal coalition size (middle), and the expected time the jack-up is idle under a given coalition size (right). The failure rate of blades does not affect the optimal coalition size and only slightly affects the expected yearly costs. The reason is that blades have a short replacement time, namely 24 h compared to 144 h for a gearbox, and thus a failure of a blade has a small impact on the workload for the jack-up. In addition, blade replacements are relatively easy to schedule as only a short time window with good weather conditions is required. Notice that larger coalitions are more sensitive to an increase in the failure rate of blades due to the low fraction the jack-up is idle (2% for six partners compared to 11% for five partners given the base case failure rate of 0.55).

In contrast to the failure rate of blades, the failure rate of gearboxes has a considerable effect on the yearly costs because it is the most expensive component and requires a long time window to replace, implying that delays due to weather restrictions are more likely for such campaigns. As a result, the optimal coalition size rapidly increases if the failure rate reduces. However, coalitions that are too small because the failure rate is lower than expected are still cost-effective compared to

leasing. For instance, if the failure rate is much lower, say 2.00 instead of 5.48, then the coalition of the base case with five partners still realises cost savings of 39% compared to leasing (4.9 million versus 6.2 million). However, the yearly costs can be reduced to 4.2 million by expanding the coalition to seven partners. A coalition of five partners is also cost-effective if the failure rate is much higher than expected. However, the yearly costs of larger coalitions are considerably more sensitive to higher failure rates due to the possible congestion that arises in such scenarios. Thus, if there is a high uncertainty of the estimated failure rate, it may be better to be conservative and form a somewhat smaller coalition, also because it may be easier to expand an existing coalition than to reduce the number of partners. Summarising, the gearbox is the most critical component and the failure rate strongly interacts with all performance measures. However, sharing with four to six partners is cost-effective for all failure rates.

Fig. 8 shows the effect of the replacement time of the gearbox on the expected yearly costs (left), the optimal coalition size (middle), and the time the jack-up is idle under a given coalition size (right). The effects of the replacement time of the blades are negligible and are therefore not shown. This is as expected since blades have low failure rates. Considering the gearbox, a coalition of five partners is optimal if the replacement takes between 122 and 170 h (the base case value is 144 h). Shorter replacement durations do not significantly reduce costs if the coalition size is kept constant, however, faster replacements allow for larger coalitions which are more cost-effective. The base coalition with five partners outperforms the leasing policy for all replacement durations. We conclude that the insights are robust with regard to the replacement duration for all components.

4.3.2. Distances, jack-up capacity, and travel speed

Fig. 9 shows the effect of distances between ports and their corresponding wind farm on the yearly average costs per wind farm. Only the yearly costs are shown since the optimal coalition size and the optimal batch threshold are not affected by this parameter. For small coalitions (i.e., up to five wind farms), the effect on the yearly costs is small whereas for larger coalitions the effect becomes clearly visible. An increase in distance obviously increases fuel costs and the travel duration towards the wind farm. However, fuel costs are low compared to the total yearly costs. For instance, if the distance to the wind farm equals 100 km then fuel costs are only 4.0% of the total yearly costs (0.26 million out of 6.52 million). Furthermore, a longer travel duration directly implies an additional delay of maintenance and thus longer downtime. However, the additional downtime is negligible on the average downtime of 1367 h as the travel duration increases from over an hour to around 5 h if we increase the distance from 25 km to 100 km.

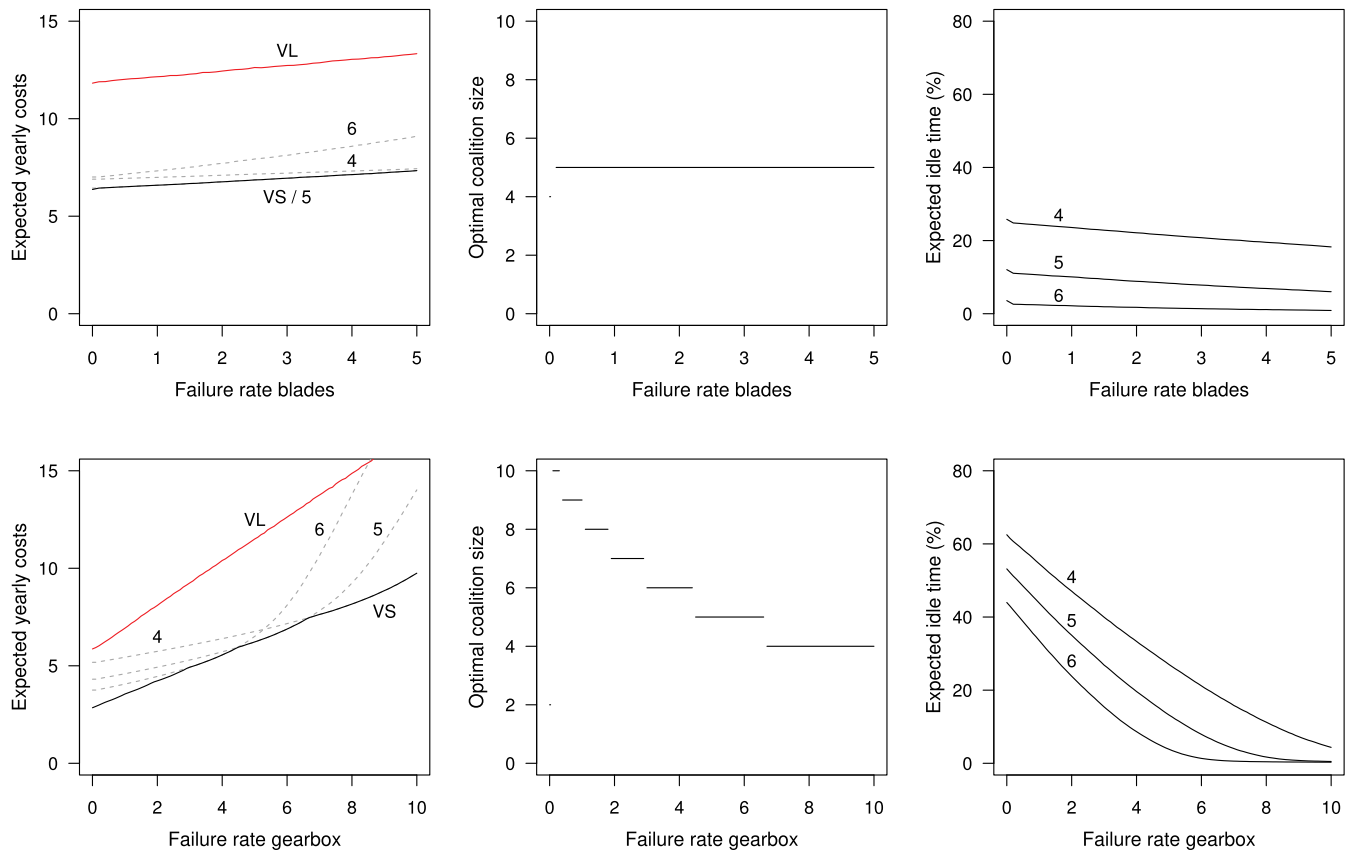


Fig. 7. Effect of the failure rate of blades (top) and gearboxes (bottom) on the expected yearly costs in millions (left), the optimal coalition size (middle), and the expected time the jack-up is idle (right). VL indicates the leasing policy, VS the sharing policy with the optimal coalition size, and numbers indicate a given coalition size.

Note that, for small coalitions, the additional delay is not likely to accumulate with delays of other wind farms since the jack-up is expected to be 10.6% idle for a coalition of five partners. For larger coalitions (i.e., six and more), the idle time rapidly diminishes and thus the delay in one wind farm is likely to cause an additional delay for future jobs. This explains why the yearly costs of larger coalitions react more heavily to the distance between ports and their corresponding wind farms. We conclude that resource sharing is beneficial both for wind farms close to the harbour from which these are served and for wind

farms located far offshore.

Similar results are observed for the distances between different ports. However, the effect of distances between harbours is smaller than for the distances to the wind farms because the weather restrictions to travel between ports are less restrictive than the weather restrictions for offshore operations. An important conclusion is that resource sharing policies are also cost-effective for harbours that are located further apart.

The base case studies a jack-up that travels with 11 knots. However,

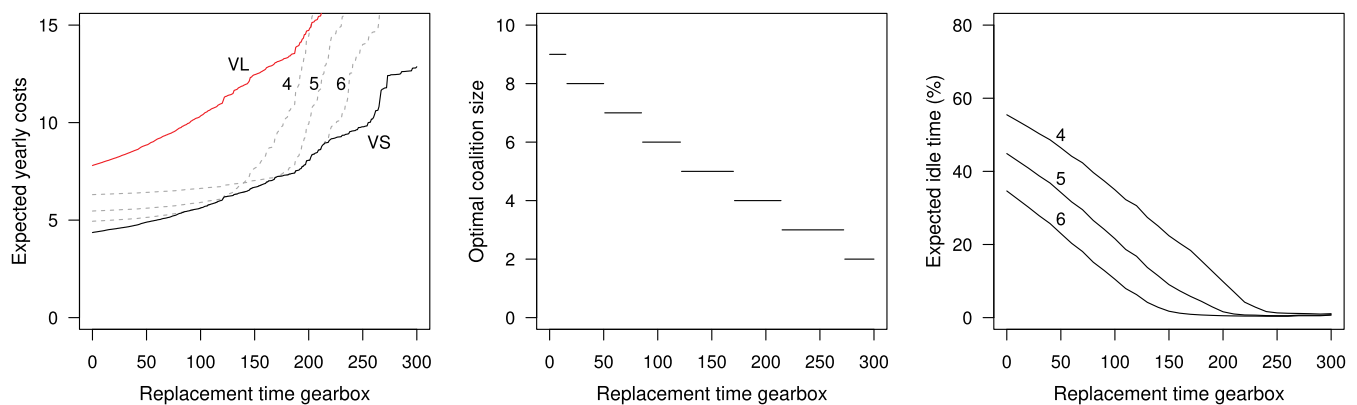


Fig. 8. Effect of required time (in hours) to replace a gearbox on the expected yearly costs in millions (left), the optimal coalition size (middle), and the expected time the jack-up is idle (right). VL indicates the leasing policy, VS the sharing policy with the optimal coalition size, and numbers indicate a given coalition size.

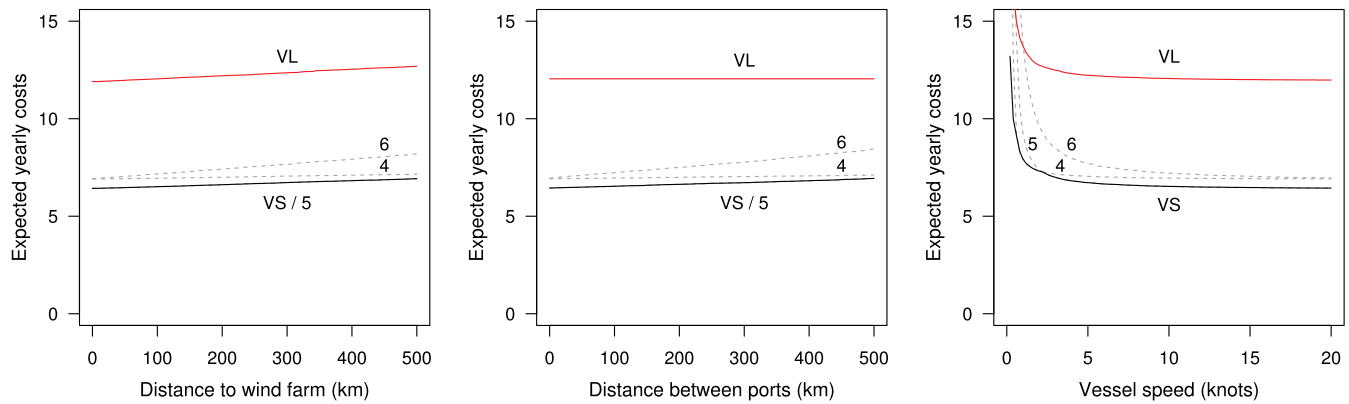


Fig. 9. Effect of distances between harbours and their corresponding wind farm (left), distances between adjacent harbours (middle), and the vessel speed (right) on the expected yearly costs in millions. VL indicates the leasing policy, VS the sharing policy with the optimal coalition size, and numbers indicate a given coalition size.

operators can decide to travel at a lower speed to save fuel, and also travel speed can be considerably affected by the current the vessel faces during transit. To examine whether this affects our insights, we consider travel speeds ranging from 0.2 to 20 knots in steps of 0.2 knots, see Fig. 9 (right). Although such an approach does not include uncertain currents a vessel experiences in practice, a travel speed of 5 knots presents a worst-case scenario in which the jack-up always faces adverse current while higher vessel speeds can be considered as a best-case analysis. Reducing the vessel speed to 5 knots increases the expected total yearly costs under the VS policy by 3.1% (from 6.5 million to 6.7 million) and under the leasing policy by 1.5% (from 12.0 million to 12.2 million). The optimal coalition size and the optimal batch threshold for the leasing policy are not affected. Similar to the distances between ports and their wind farms, the VS policy is slightly more sensitive to the travel speed since, under the VS policy, a delay in one wind farm may propagate to the next one when there are jobs available for various wind farms. Moreover, for extremely low vessel speeds (i.e., below 2.5 knots), there will almost always be a queue of jobs and, as a result, the yearly costs rapidly increase due to accumulating delays for future jobs. Since both the optimal coalition size and optimal batch size threshold for the leasing policy are not affected by the vessel speed, except for unreasonably low values below 2.5 knots, we conclude that the insights are robust with regard to varying vessel speeds, which may be caused by adverse current conditions.

4.3.3. Weather restrictions

Next, we examine the effect of weather restrictions on the yearly costs and the optimal coalition size. Fig. 10 shows the effect of the maximum allowed wind speed at hub height during a replacement. A lower wind limit results in more delays due to the weather restrictions, thereby decreasing the idle time of the jack-up and increasing yearly costs. Sharing a jack-up with the optimal coalition size is cost-effective compared to leasing for all considered maximum wind limits. However, if conservative limits are used (e.g., 13 m/s at hub height), then the yearly costs can be more expensive than leasing if the coalition is too large. Note that these results hold for an electricity price of 100 euros per MWh. If we examine the same results with an electricity price of 50 euros per MWh, then coalition sizes of four to six partners outperform the leasing policy for all maximum wind speeds.

The survivability restrictions have no significant effect on the yearly costs nor on the optimal coalition size. The main reason is that the restrictions for both jacking and lifting are much tighter, and as a result, it is unlikely that survivability restrictions are violated around a time interval in which jacking and lifting are possible.

4.3.4. Costs parameters and others

Currently, the price per MWh received by wind farm owners is kept artificially high by subsidies. However, newer wind farms might receive smaller, or even no, subsidies. Fig. 11 shows the effect of other power prices, ranging from 0 to 200 euros per MWh. The total yearly costs obviously increase if the power price increases due to higher revenue losses. However, the optimal coalition size equals five wind farms for all prices between 50 (which is a reasonable estimate of current electricity prices without subsidy) and 190 euros per MWh (higher than the highest subsidy price given in the Netherlands). It follows that coalitions can be formed without high risks towards changing energy prices. If the electricity price drops below 50 euros, then longer downtimes are acceptable. This allows for larger coalitions that are clearly more cost-effective than smaller coalitions, mainly because they realise almost a maximum jack-up utilisation. For instance, for a price of 35 euro per MWh, the optimal coalition size equals six wind farms, which results in a jack-up utilisation of 98% compared to 90% for a coalition of five partners. Finally, the power price is one of the few parameters that affects the optimal batch threshold for the leasing policy (see most right figure). For low prices, it is beneficial to cluster jobs into larger campaigns with three jobs. For extremely high prices, it is even cost-effective to charter a jack-up for a single job.

Besides the parameters discussed above, we changed the fuel price from free to ten times as expensive as in the base case, which does not affect the optimal coalition size nor the optimal batch size threshold. This is as expected since the fuel costs are small compared to the other cost factors such as replacements costs and revenue losses.

Recall that delays can be used to wait for suitable weather conditions, and that the maximum delay that is allowed between offshore activities is set to 24 h based on our interviews with experts. We ranged this parameter from 6 to 72 h, which also does not affect our insights. It follows that resource sharing cannot be made more efficient by allowing for longer offshore delays.

Finally, recall that the base case capacity is three replacements per campaign. We checked whether it is beneficial to consider a jack-up with a higher capacity. Larger campaigns are only beneficial if there is considerable congestion in the system, which does not occur in the optimal coalition size. As a result, increasing the jack-up capacity does not result in improved performance and does not affect the decision variables.

4.4. Case study

To illustrate the benefit of resource sharing to wind farm service providers and other practitioners, this section applies the policies to actual wind farms from the Western North Sea area, see Fig. 12. Four

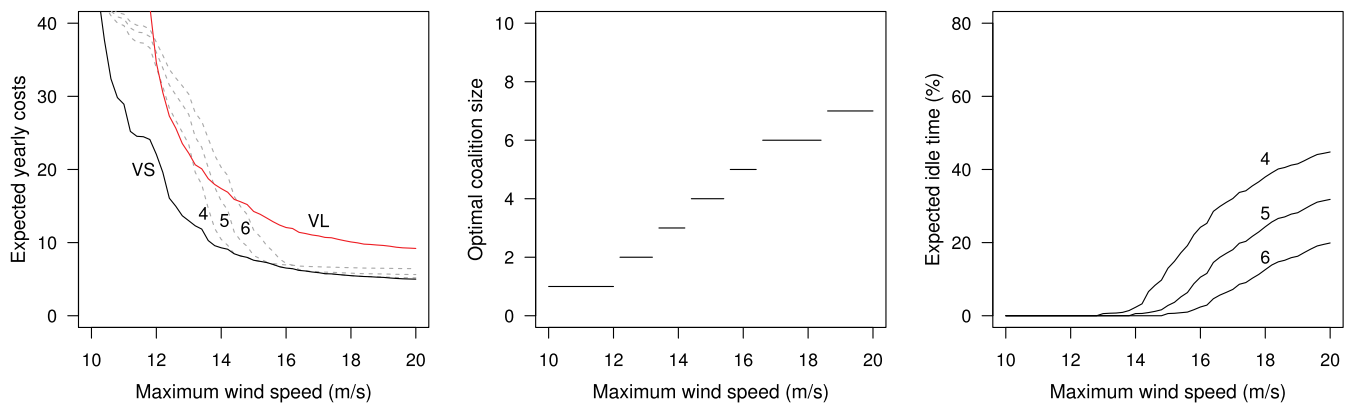


Fig. 10. Effect of the maximum allowed wind speed (in m/s) at hub height during a replacement on the expected yearly costs in millions (left), the optimal coalition size (middle), and the expected time the jack-up is idle (right). VL indicates the leasing policy, VS the sharing policy with the optimal coalition size, and numbers indicate a given coalition size.

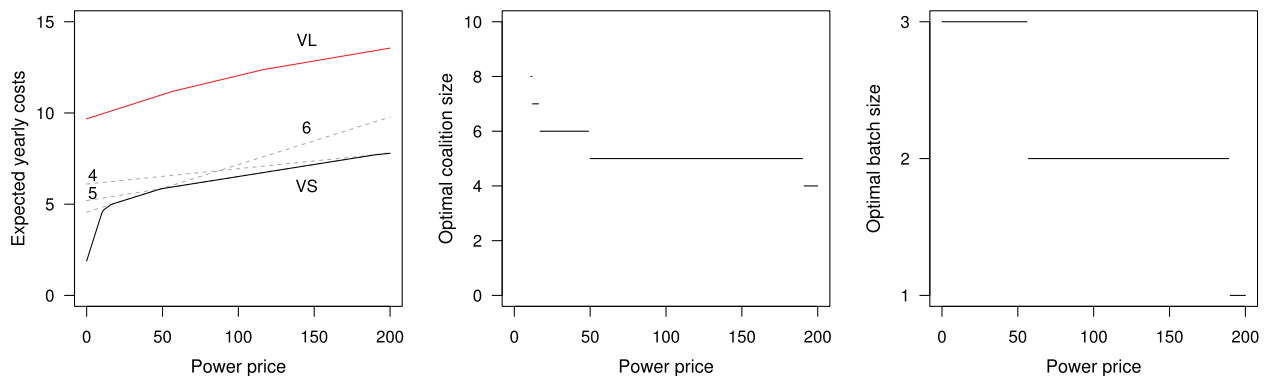


Fig. 11. Effect of the received power price (in Euros per MWh) on the expected yearly costs in millions (left), the optimal coalition size (middle), and the optimal batch threshold (right). VL indicates the leasing policy, VS the sharing policy with the optimal coalition size, and numbers indicate a given coalition size.

possible collaboration modes with Dutch (OWEZ, Princess Amalia, and Eneco Luchterduinen), Belgian (Thorntonbank and Belwind), and British (Greater Gabbard and Gunfleet Sands) wind farms are considered. The first mode considers collaboration between Dutch wind farms only, the second includes Dutch and Belgian wind farms, the third explicitly zooms in on the collaboration between wind farms in a

specific setting where wind farms are located somewhat in between harbours, which are located at opposite coasts (Great Britain and Belgium), the fourth mode includes all wind farms and harbours. Table 5 provides an overview of the studied wind farms and harbours, and the four collaboration modes.

In order to obtain clear-cut results, we assume that all parameters

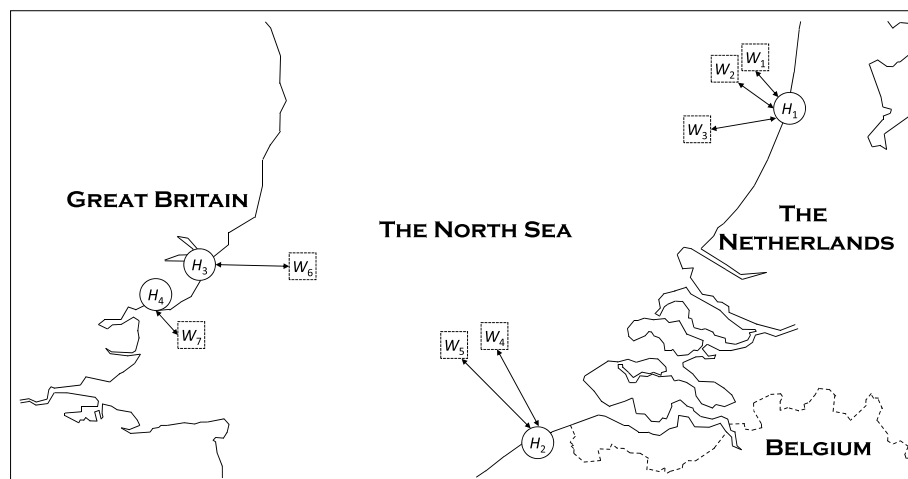


Fig. 12. Western North Sea case study.

Table 5

Overview of the wind farms and their corresponding harbours, and the possible collaborations.

Wind farm	Turbines	Harbour	Coll. I	Coll. II	Coll. III	Coll. IV
W_1 OWEZ	36	H_1 IJmuiden	×	×		×
W_2 Princess Amalia	60	H_1 IJmuiden	×	×		×
W_3 Eneco Luchterduinen	43	H_1 IJmuiden	×	×		×
W_4 Thorntonbank I, II, III	54	H_2 Zeebrugge		×	×	×
W_5 Belwind	55	H_2 Zeebrugge		×	×	×
W_6 Greater Gabbard	144	H_3 Harwich			×	×
W_7 Gunfleet Sands	48	H_4 Brightlingsea			×	×

Table 6

Results of the various collaboration modes. Total costs are given as the total yearly cost for the entire coalition, i.e., not per wind farm.

	Total costs	Cost difference	Availability	Mean downtime	Max downtime	Vessel utilisation
<i>Collaboration I (139 turbines)</i>						
Vessel leasing	€ 33.58·10 ⁶	-	99.7%	8973 h	19856 h	-
Vessel sharing	€ 23.96·10 ⁶	- 28.7%	99.8%	3218 h	16068 h	53.7%
Vessel + harbour sharing	€ 23.96·10 ⁶	- 28.7%	99.8%	3218 h	16068 h	53.7%
<i>Collaboration II (248 turbines)</i>						
Vessel leasing	€ 56.67·10 ⁶	-	99.7%	8914 h	19957 h	-
Vessel sharing	€ 31.89·10 ⁶	- 43.7%	99.1%	7482 h	26590 h	87.5%
Vessel + harbour sharing	€ 31.87·10 ⁶	- 43.8%	99.1%	7448 h	26521 h	87.4%
<i>Collaboration III (301 turbines)</i>						
Vessel leasing	€ 69.36·10 ⁶	-	99.4%	8835 h	20859 h	-
Vessel sharing	€ 40.71·10 ⁶	- 41.3%	97.9%	13998 h	39591 h	96.2%
Vessel + harbour sharing	€ 40.59·10 ⁶	- 41.5%	98.0%	13871 h	39398 h	96.2%
<i>Collaboration IV (440 turbines)</i>						
Vessel leasing	€ 102.94·10 ⁶	-	99.5%	8894 h	20429 h	-
Vessel sharing	€ 140.28·10 ⁶	+ 36.3%	82.3%	96288 h	170439 h	99.7%
Vessel + harbour sharing	€ 139.84·10 ⁶	+ 35.9%	82.4%	95809 h	169851 h	99.7%

are similar to the base case, with the exception of wind farm size and geographical distance between wind farms and harbours, and between harbours. Results are given in Table 6. Again we see that resource sharing can lead to significant benefits compared to vessel leasing, both for small coalitions (i.e., coalition I) and for larger coalitions (i.e., coalition II and III). As expected, if more wind farms are added to the coalition, then vessel utilisation, mean downtime, and maximum downtime increase, and the availability decreases. However, from a cost perspective, a slight availability reduction is acceptable as is seen in collaboration II and III. Coalition II and III show that coalitions with harbours that are located far away from each other are possible. Coalition I indicates that smaller coalitions have the potential to both reduce costs and simultaneously increase the availability, which can be preferred from a production point of view. Moreover, the largest coalition is not cost-effective, mainly due to the long transit times between the British and Dutch harbours and because of the excessive demand for the jack-up.

The benefits of VHS compared to VS are small for all collaborations but largest in collaboration mode IV. The explanation is that in this setting the total size of the coalition in terms of wind turbines is rather large (and clearly too large from a cost point of view). This leads to a significant number of failures in the system, which at times can lead to congestion. The VHS policy is only beneficial if congestion occurs because then it becomes important to eliminate unnecessary transits between harbours. Note that in this case the jack-up vessel is almost fully utilised, which is undesirable from a cost point of view as discussed in the results of the base case.

5. Discussion

5.1. Main findings

This paper evaluates whether the sharing of jack-up vessels and harbour facilities between offshore wind farm service providers could

be part of a cost-effective O&M strategy. By sharing the cost of employing a jack-up vessel, it could be possible for service providers to lower cost compared to the vessel leasing (VL) policy. Under VL, the cost of maintenance is a variable cost that depends, among others, on the chartering and lease time. Under the resource sharing policies (vessel sharing, VS and vessel + harbour sharing, VHS), a part of these costs of maintenance becomes a fixed cost. In essence, purchasing a jack-up vessel provides an economy of scales: the larger the collaboration, the lower the individual share of the fixed capital [25].

A base case setting was studied with multiple wind farms (each consisting of fifty 3 MW turbines), located 100 km from each other and their corresponding harbours. The results show that vessel sharing policies can realise a significant cost reduction compared to vessel leasing, provided that the right number of service providers participate. Furthermore, we find that resource sharing increases turbine availability and, naturally, increases jack-up vessel utilisation. Nevertheless, the lowest cost case (with five participating wind farms and service providers) shows that some revenue losses and jack-up idle time should be accepted to maximise flexibility and minimise the average yearly cost per wind farm. Cost benefits up to 45% can be achieved when wind farms collaborate. However, if too many service providers enter the coalition (i.e., eight or more) demand for maintenance services becomes too high, resulting in congestion and increased turbine downtime.

An interesting finding in the base case is the limited impact of transit time on jack-up utilisation and cost, as the existing literature suggests that the impact could be large [35]. It was found that relative to other factors (e.g., mobilisation time and waiting time due to weather delays) the impact is rather small. This explains why the benefits of the VHS policy, which main goal is to reduce travelling time between harbours by sharing harbour facilities for (de)mobilisation, were found to be rather small. The sensitivity analysis showed that the benefits of resource sharing are robust to (i) distance between wind farms, (ii) distance between wind farms and harbours, and (iii) number of turbines per wind farm.

5.2. Practical implications

The results are relevant for practitioners and policy makers. First and foremost, given the increased future investments in offshore wind and continuing societal pressure to remain low costs of energy generation, it would be beneficial for service providers to consider investing collectively in jack-up vessel purchasing. To keep costs at a minimum and ensure high turbine uptime, there exists an ideal number of service providers participating in the resource sharing coalition, and this number depends on factors such as wind farm size. This paper sheds light on the trade-offs between sharing the fixed and variable cost of owning a jack-up vessel among participating members, and the jack-up utilisation and downtime due to system congestion. Making additional investments into harbour sharing, in contrast, seems to be much less effective for reducing the cost of maintenance.

In logistics and transportation the concept of resource sharing, as introduced in this paper, is generally identified as a type of horizontal collaboration. However, several challenges and barriers should be overcome for such collaborations to be effective. The review given by Cruijssen et al. [8] mentions in particular coordination in trust among partners, ICT, negotiation, and reliability of cost and profit allocation models. Regarding the latter, the resource sharing concept such as presented in this paper would necessitate sophisticated rules for cost and benefit sharing, next to rules for the prioritisation of jobs (see below). Costs and benefits are determined by several factors, which in practice may differ from wind farm to wind farm. Wind farm operations and maintenance may differ in terms of cost of delay (which is affected by the price of energy and turbine size) and the maintenance demand levels (which is affected by wind farm size, turbine size and turbine failure rates). Also, distance between harbours and wind farms are unlikely to be symmetric in practice. Decision rules should ideally incorporate those factors, but do not yet exist in the literature. However, generic decision frameworks are available [28,33]. Also, a wide range of profit (or cost) allocation methods have been developed [17,32,48,50]. Regarding the ‘softer’ issues related to trust building and information sharing, it may be advisable for operators to follow a path of incremental rather than radical change. In this light, engaging in a pilot project (facilitated, for instance, by joint leasing) would allow coalition members to experience the benefits and downsides of resource sharing, without far-reaching commitments. In addition, this may identify legal and customs issues. Nevertheless, resource sharing in the way represented in this paper would require commitment and risk-taking. We hope to have shown in this paper that resource sharing is worth considering.

5.3. Limitations and future research

As is common in simulation studies, some simplifications were needed. Most of these simplifications are expected to have little impact on the results, such as the exclusion of spare part management (which should impact vessel leasing and resource sharing equally). In this study, we assumed a constant failure rate for each turbine component. Although these failure rates are averages based on reported failure data, they may vary from year-to-year and from country-to-country [21]. In addition, new turbine technology could exhibit other failure behaviour, which could influence the usefulness of resource sharing. Efforts should be made to better understand the failure patterns of turbine components. Such research would substantially increase the practical value of all offshore wind farm O&M models that rely on accurate system failure modelling.

Another limitation of the model is the exclusive application of the first-come-first-serve principle. In reality, it would make sense to cluster maintenance jobs [31], by keeping the jack-up at one location to complete multiple replacements before transiting to the next location, irrespective of the order of failures. Note that this would primarily improve the performance of the resource sharing policies since wind

farms operate independently under the vessel leasing policy. Relaxing the first-come-first-serve policy would also make room for more advanced routing policies, for instance, jobs in a wind farm with harsh weather conditions can be postponed. Importantly, clustering jobs for multiple wind farms in a single trip would complicate onshore logistics in case these activities are centralised (e.g., mobilisation and loading parts in one particular harbour). Also technicians might need to be capable of servicing different turbine brands.

Furthermore, we consider the same weather realisation at all locations, which is possible because we only consider a first-come-first-served policy, implying that the order in which wind farms (and their corresponding harbours) are visited are determined by the sequence in which turbines fail, and as a result, only the weather realisation at the next wind farm or in between two harbours affects the planning until the next job is finished. However, when more advanced policies are considered (e.g., one that can postpone jobs in a wind farm with poor weather conditions), it becomes important to take into account different weather realisations at different locations as one could allow the jack-up to adjust its planning accordingly. We remark that this only benefits the sharing policies and not the leasing policies, and thus the possible cost savings by co-owning a jack-up vessel will increase if more advanced scheduling policies are considered.

Finally, in this study maintenance is triggered by failure of components. Although this still appears to be the dominant maintenance policy for many components, condition-based maintenance is expected to have a significant impact on maintenance planning when properly implemented [23]. In particular, it could help planning the use of jack-up vessels, and allow for better prioritisation and clustering of jobs, possibly across wind farms. Furthermore, if condition information is available, both the sharing and the leasing policies can be improved by incorporating condition-based production decisions during periods with high workloads for the jack-up or during the chartering time [46]. For future research, resource sharing can also be extended to small component replacement, which considers additional factors such as time-based maintenance schedules and opportunistic maintenance.

Acknowledgements

This study has been done as part of the research project ‘Sustainable Service Logistics for Offshore Wind Farms’ (project number 438-13-216) funded under the Dutch NWO-Dinalog program ‘Sustainable Logistics’. We would like to thank our consortium partners for providing relevant data and information for this study, particularly Siemens Gamesa and ECN part of TNO.

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